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**TOWARD THE IDEAL MILITARY
AVIATION SUNGLASS**

J. S. Marsh, W. B. Cushman, and L. A. Temme

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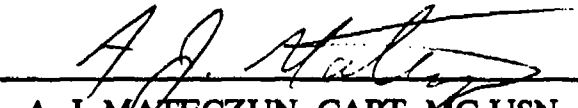
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13. ABSTRACT (Maximum 200 words) Sunglasses and sunvisors affect vision, but can they actually improve it? The effects of sunglasses on vision were modeled considering: 1) Duntley and Middleton's theoretical treatment of the propagation of light through the atmosphere; 2) the dependence of light scatter on wavelength; 3) Blackwell's extensive "Tiffany" data base describing human visual sensitivity to incremental, contrasting spot stimuli; and 4) human spectral sensitivity. With these factors, sunglass and visor characteristics were identified that maximize the range for detection of small objects. The ideal sunglass or visor thus identified increases the range at which objects can be detected by an average of 5% compared to the naked eye. By comparison, the standard 12% neutral filter currently used for aviator sunglasses decreases naked eye range by about 5%. This paper provides a theoretical framework that could be used in the design and evaluation of sunglasses and visors in environments where vision is critical.					
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SUMMARY PAGE

THE PROBLEM

The current standard military aviation sunglass, a neutral gray filter, was designed to minimally affect vision and to be as widely useful in as many environments as possible. This sunglass was not designed to optimize any particular visual task in any particular environment. In this paper we have specifically attempted to optimize a sunglass for the aviation environment. We have formulated a mathematical model of the physical and physiological factors relevant to the detection of a black, airplane-sized target seen through a reasonable approximation of the atmosphere and against a reasonable approximation of the sky. We calculated the amount of color (wavelength) dependent scatter in the atmosphere and how much this scatter would reduce contrast between the target and the sky background. This contrast, the inverse relationship between target distance and apparent size, and published measurements of human size/contrast detection capabilities form the basis for predicting target detection distance.

Threshold target detection distances were calculated for the unaided eye and for standard military sunglasses using several atmospheric visibilities (meteorological ranges) from very good to very bad. We then identified the spectral filter that would optimize target detection distance for each of these visibility conditions. This spectral filter is the theoretical ideal sunglass for the particular conditions examined.

FINDINGS

1. The results of our model indicate that under all but the poorest conditions of visibility, the standard military sunglass, in comparison to the unaided eye, produced a reduction in target detection distance ranging from 1.9% to 7.2%. The greater the meteorological visibility, the greater the visual loss through the standard military sunglass.
2. The model also shows that under all visibility conditions the optimal sunglass, in comparison to the unaided eye, produced an increase in target detection distance ranging from 4.4% to 5.9%.
3. Finally, the model indicates that under all visibility conditions the theoretically ideal sunglass will produce target detection distances from 6.5% to 11.2% greater than the target detection distances of the standard military sunglass. The better the meteorological visibility, the more the ideal sunglass outperforms the standard sunglass.

RECOMMENDATIONS

1. The present study, which was totally theoretical, produced a set of predictions or visibility calculations. Experiments should now be conducted to evaluate target detection in the field, in a real atmosphere. Laboratory studies conducted within walls will not be adequate because the effects of sunglasses on vision depend on seeing through kilometers of atmosphere.
2. The integration of sunglasses into an operational environment raises many issues of compatibility. The chromatic composition of the visual world will be altered while wearing the ideal sunglasses described here. While there will almost certainly be no permanent effects on color vision, the operational significance of changes in color perception should also be evaluated.
3. The overall procedure developed in the present study may be applied to any of several different kinds of tasks where distant vision is crucial, that is, tasks that depend on detecting small differences in contrast

between a target and a background. Spectral filters may then be specifically designed to enhance the target-to-background contrast differences and improve the performance of such tasks.

4. The results of this study could be incorporated into a military specification (MILSPEC) for sunglasses by adding the following requirements.

- a. The sunglass should permit detection of a standard target under standard conditions at ranges at least as great, or $x\%$ greater, than that permitted by the naked eye.
- b. The sunglass should permit acuities within 90% of the maximum.
- c. The sunglass should pass no greater than 30% of incident light.
- d. The sunglass should be compatible with head up displays (HUDs) and other instrumentation.

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INTRODUCTION

The current specifications for U.S. military sunglasses have evolved from activities initiated during the Second World War by the Army-Navy Vision Committee of the National Research Council, subsequently called the Armed Forces National Research Council Vision Committee (NRC COV). Sunglasses remained an active topic of NRC COV discussion up to about the mid 1950s. The minutes of the NRC COV meetings make it clear that almost every aspect of sunglasses has been thoroughly considered. The present report addresses only two of the many issues affecting vision in military aviation: the optical density and spectral transmittance of sunglasses and visors. The current military standard specifies sunglasses to have a transmittance of $15\% \pm 2\%$ (optical density of about 0.8) and to be approximately flat throughout the spectrum (MIL-S-25948J). These neutral density sunglasses decrease the amount of light reaching the eye but leave the spectral content proportionally unchanged. The effects of filter or sunglass density on vision have been studied extensively. For example, various workers have studied visual acuity and resolution (1,2), spot detection (3), critical flicker frequency (4), dark adaptation (4,5), color and color perception (6,7).

Classic data demonstrating the relationship between luminance and acuity are shown in Fig. 1 (8). As luminance increases, so does acuity, up to a point. This asymptotic dependence of visual performance on luminance is characteristic of many types of visual function and makes intuitive sense; there are limits to visual performance. Maximal acuity, about log 0.25 (approximately equivalent to 0.5 min of visual angle), is reached with retinal illuminances of between log 1.0 and log 3.0 trolands.

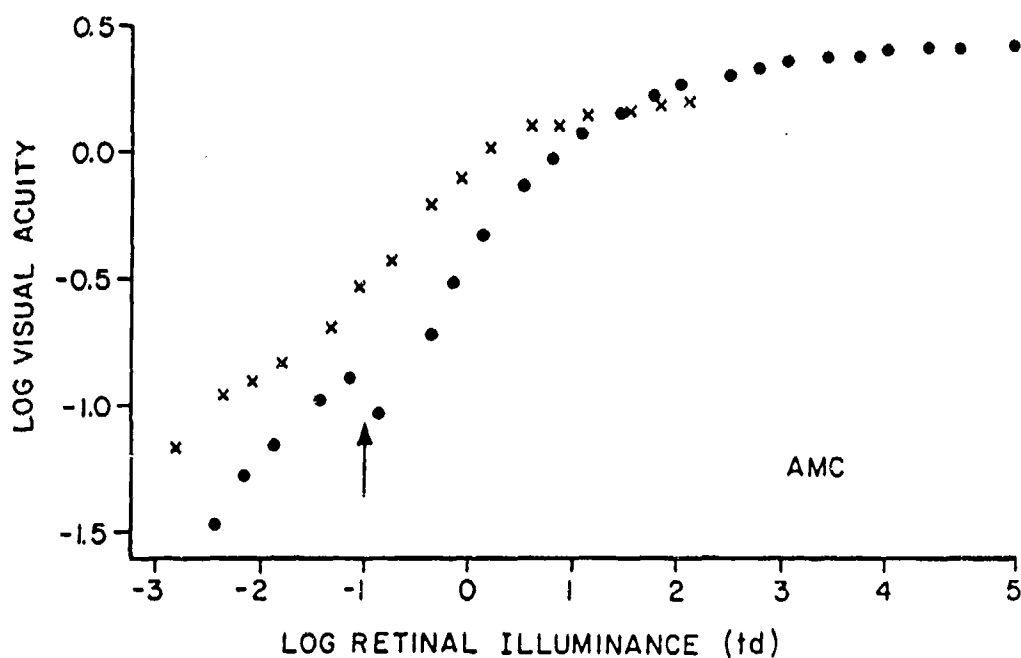


Figure 1. The relation between luminance and acuity; x = grating target; • = Landolt ring target. Arrow indicates point at which subject started using central fixation for Landolt ring target. (From *Handbook of Perception, Vol V*, p 237, 1975. Ed. by Edward C. Carterette and Morton P Friedman. Data from Schlaer, S., "The relationship Between Visual Acuity and Illumination." *Journal of General Physiology*, Vol. 21, pp. 165-188, 1937. Reprinted with permission.)

Typical daytime sky luminances encountered in aviation are reported to be between 3,400 and 34,000 cd/m^2 (10). It would be nice to directly relate this measure to the "trolands" above, but, unfortunately, there are some ambiguities. The cd/m^2 refers to the luminance of the object, while the troland refers to the amount of light from the object that actually reaches the receptor surface, the retina, inside the eye. A principal source of the difference is pupil size; people looking at the same object will have different pupil sizes and, therefore, the amount of light from the same object actually reaching the retinas will be different (11). On the average, 3,400 cd/m^2 is about 10,000 trolands or 4.0 log trolands (12). The data in Fig. 1 show that this is well above the level where increases in luminance improve visual acuity.

According to the data of Fig. 1, the standard military sunglass probably has no effect on visual acuity at typical daytime luminances. The sunglasses transmit roughly 3.17 log trolands. In fact, these data indicate that sunglasses that reduce retinal illuminance to 10 - 100 trolands would have little effect on acuity. Such sunglasses would have a transmittance of 1.0 - 0.1%.

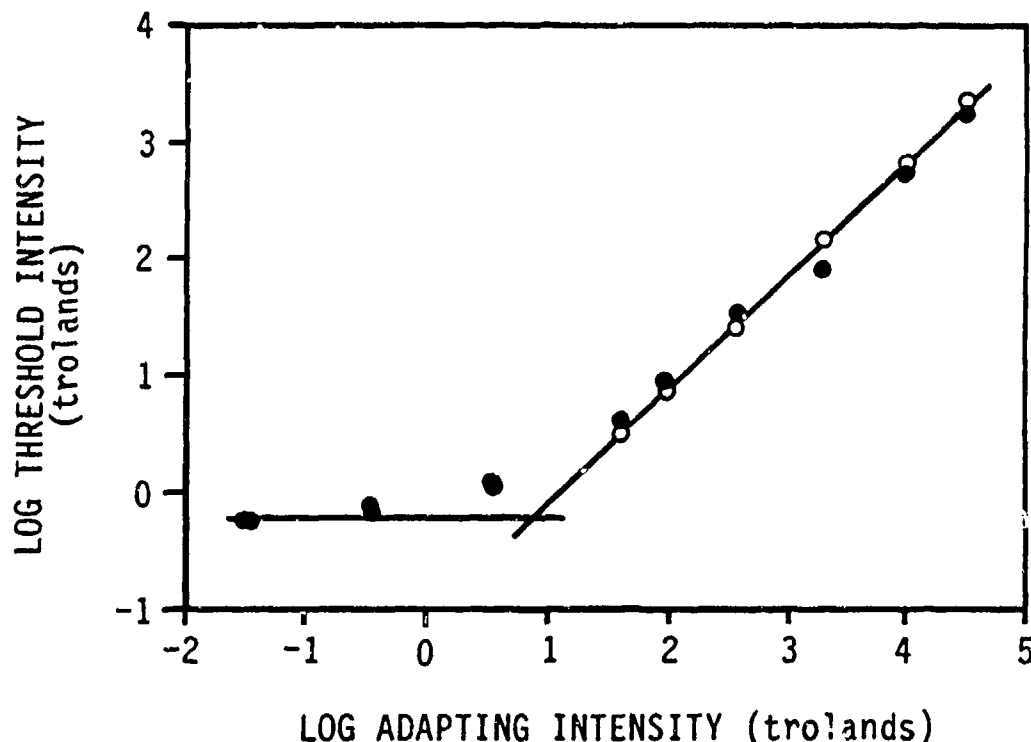


Figure 2. Detection threshold vs intensity for foveal cone system. The data form a straight line with a slope of zero at low intensities, but at higher intensities the slope becomes one. A slope of one conforms to the Weber-Fechner law: $I_T = k \cdot I_A$ where I_T is the threshold intensity, k is a constant and I_A is the adapting intensity. (From Hood, D.C. and Finkelstein, M.A., "Sensitivity to Light." In K.R. Boff, L. Kaufman, and J.P. Thomas (Eds.) *Handbook of Perception and Human Performance, Vol. 1, sensory processes and Perception*, John Wiley and Sons, Inc. New York, NY, 1986, pp. 5-1 to 5-66. Data from Moeller, G.G., "Frequency of Seeing Functions for Intensity Discrimination at Various Levels of Adapting Intensity." *Journal of General Physiology*, Vol. 34, pp 463-474, 1951. Reprinted with permission.)

A distinction must now be made between three related phenomena: acuity, contrast, and contrast threshold luminance. The acuity data above assume a high contrast, which is not altered by the presence of a neutral density filter, but, the human contrast threshold is, indeed, increased as luminance level is reduced. This is why our model shows a decrement in performance for the standard aviator sunglass versus the naked eye.

The impression we have from reading the NRC COV minutes is that the principal consideration for defining a military sunglass standard was that it be put into widespread use across all the military services. To achieve the goal of widespread usefulness, the sunglass was designed specifically to have as little effect on vision as possible, and to minimize the effects on color discrimination and color matching. No effort was made to optimize vision on any particular task (13,14). It may be argued that current military aviator sunglasses increase comfort and visual efficiency by reducing the amount of glare and the ambient levels of light reaching the eye. If the principal role of the sunglasses is to increase comfort and reduce glare, then the data in Fig. 1 and known sky brightness measures suggest that sunglasses designed for aviation use could be made more effective simply by being made darker. We must again emphasize, however, that the data of Fig. 1 assume a high-contrast target. Glare is a complex issue. Figure 2 (15) shows that there is little scientific support for the idea that sunglasses make it easier to see targets in a visual environment with glare (15,17). The horizontal axis indicates luminance of a large background field, while the vertical axis is the threshold luminance of a small test spot superimposed on the background. As the luminance of the background field increases, it affects sensitivity to the test flash; the more light in the background, the more light is needed in the test flash to detect it. There is a direct proportionality, which is indicated by the fact that the increment threshold curve has a slope of 1.0. This is the well known Weber ratio or Fechner law of classical psychophysics (15,17). The effect of glare very likely parallels these experimental observations. A spot of light is to be detected against a background generated by the glare source. Putting a filter or a neutral sunglass in front of the eye reduces the background glare, but it also reduces the test target luminance proportionally, resulting in a zero net increase in detectability.

The literature contains a great deal of discussion about the role of color in sunglasses and whether or not colored filters can improve vision and visual performance (18-24). Much of this work was motivated by anecdotal and subjective reports of the beneficial effects of yellow tinted lenses, so-called "shooter's glasses." However, most of the studies demonstrated little, if any, benefit to be derived from these filters. Moreover, colored sunglasses will alter the colors seen through them and can reduce the visibility of certain parts of the spectrum; particularly for individuals with color vision deficits (18,19). Because of these possible effects, and since no particular benefit was seen to be gained by incorporating color, the current standard military sunglass is gray, approaching spectral neutrality (7,13,14).

We suggest that there are reasons to reconsider the role of color in sunglasses to be used by military aviators. Our reasoning is based on the well-known fact that the shorter wavelengths of light are subject to more atmospheric scattering than long wavelengths. This scattering, in turn, is responsible for image degradation. Theorizing that an image could be improved by limiting those wavelengths that scatter most, we constructed a physical model to support this theory. We have produced a design for the ideal sunglass according to this criteria. The ideal sunglass out-performs both 12% neutral density visors and the naked eye by significant margins, represents a theoretically unimprovable ideal, furnishes a standard against which practically realizable sunglasses can be measured in a quantitative fashion, and furnishes a model for the design of practically realizable sunglasses.

METHOD

The model used is based on the theories of Duntley (25) and Middleton (26) on vision through the atmosphere and the Tiffany data collected by Blackwell (27) on spot detection capabilities of a large number of observers.

The primary result of our calculations is the range at which a standard target can be spotted under various atmospheric conditions and ranges using sunglasses with various spectral transmission characteristics. For comparison, the detection range was also calculated for both the standard 12% neutral density visor issued to Navy pilots and for the naked eye. The standard target was chosen to be a circular disc with an area of 25 m^2 . This target was chosen to represent the cross-sectional size of a 'typical' target a pilot might want to detect. We assume the target to be black. Assuming a black target simplifies calculations by eliminating the spectral characteristics of the target and produces maximum inherent contrast. Visual search is presumed to be made horizontally. Calculations were made for a background luminance level of 1000 ft-Lamberts, or 3426 cd/m^2 , corresponding to bright daylight illumination. The spectral characteristic of the background illumination was taken to be that of the CIE standard illuminant D65. This corresponds to typical bright daylight with direct illumination by the sun. The D65 illumination is white rather than bluish, and this simulates the condition of searching toward the horizon where the eye usually encounters a whitish haze rather than the blue of the zenith. The criterion of detectability was based on Blackwell's psychophysical measurements (27) of a grey test target presented for 6 seconds on a white background. These data give criteria on target contrast and size to make it 50% detectable in a 6 second scan time. Calculations were done for a variety of meteorological ranges (MR) of from 2 to 100 km. Meteorological range is that distance at which a large dark object, a mountain for instance, is just visible through the atmosphere. The 'ideal sunglass' is optimized for a 100 km MR because this is the range at which the standard target just becomes visible to the naked eye at about 20 km. We presume this range to be operationally most significant (28). Certain other simplifications and approximations made in the derivations and the utilization of the data will be emphasized to enhance later improvement.

COMPUTATIONAL DETAILS

We describe below the specific assumptions made and the methods used in our computations. As will soon be seen, various stages of the calculations are subject to criticism, some of which we will offer ourselves. Computational refinements may change the value of a range at which the standard target may be spotted through the sunglasses, but the range at which that target is spotted by the naked eye under the same circumstances should change by roughly the same percentage. Thus, we feel confident that those parts of the results expressed as *percentages* will be reasonably robust under refinements in the calculations, certainly more robust than the absolute values given for the ranges. The calculations are divided into two components: the psychophysical component and the physical component.

PSYCHOPHYSICAL COMPONENT

We used Blackwell's report of the Tiffany data (27) to tell under what conditions an object is just detectable. This report provides an extensive set of measurements of the ability of young female observers with excellent vision to detect circular targets of various contrasts against backgrounds of various luminances.

The data available in Blackwell's report were for observation times of 6 seconds or for essentially unlimited observation times. These were the only two choices published. We used the 6 second data as more appropriate to the expected operational conditions of aviator sunglass use, and a target detection probability of 50% to determine the detection range.

The Tiffany data is presented in tabular form in Blackwell's paper. In order to use the data more conveniently with a computer, we attempted to find a function that would adequately represent the data and serve as an interpolating function between points. We were not completely successful, due primarily to time constraints, but the function we did find seems to have its highest accuracy in the domains of interest in the calculations. The function expresses the threshold contrast C for a 50% probability of target detection as a function of angular diameter θ (the target is circular) and background surround luminance B . The selected relationship between C and B was of the Hecht type (29),

$$C = h \left[1 + \frac{a}{B^{1/n}} \right]^n \quad (1)$$

where both h and a depend on the angle θ and $n = 3$ was found to be the best choice, far better than the Moon and Spencer choice (28) of $n = 2$.

The h represents the Weber-Fechner constant in the limit of large objects. The form of h as a function of θ was suggested by work on flicker thresholds. We chose

$$h = u + \frac{v}{\theta^p} \quad (2)$$

where u and v are constants, and the best value for p was 1.5. The only suggestion in the literature that we could find for the form of the parameter a was that a be a constant, which was clearly incorrect for the data. A plot of best fit a 's versus $\log \theta$ revealed a straight line relationship except for one extreme point. Therefore, an equation of the form

$$a = r + s \log \theta, \quad (3)$$

where r and s are constants, was used. We believe that the misfit of the one extreme point accounts for most of the inaccuracy in the resulting equation.

The final form selected for the interpolating function was

$$C = h \left[1 + \frac{a}{B^{1/3}} \right]^3 \quad (4)$$

with

$$h = 0.006 + \frac{0.3}{\theta^{1.5}} \quad (5)$$

and

$$a = 0.62 - 0.27 \log_{10} \theta. \quad (6)$$

where θ is measured in minutes of arc and B is measured in ft-Lamberts.

In this report, we are looking at a circular target of 25 m^2 area, and thus with a diameter $D = 5.6$ meters. At range r , the target will subtend an angle $\theta = D/r$. The threshold contrast C thus becomes a function of r through $\theta = \theta(r) = D/r$.

Comparing the curves based on this formula against the data (Fig. 3), we see that the greatest inaccuracy is for large apparent objects, that is, large θ . Luckily, all the work in this report involves seeing the target so far away that it always subtends a very small angle, never any larger than about 10 min of arc. If it should become desirable to perform calculations for larger objects, it may be necessary to use a more accurate interpolating function than used here.

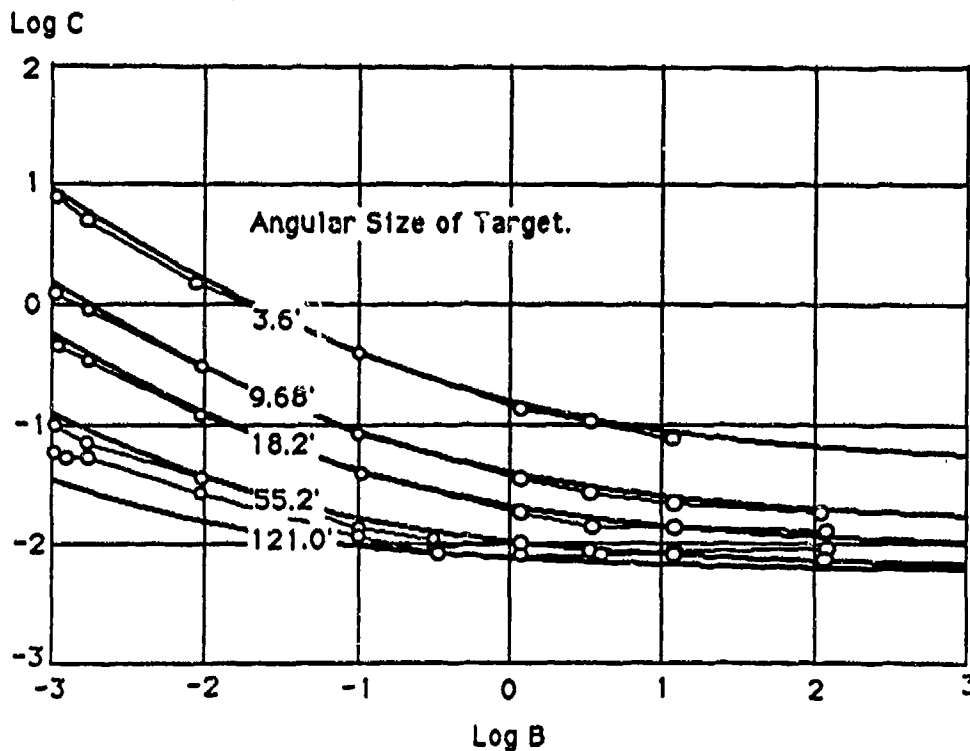


Figure 3. Threshold contrast (C) vs background luminance (B) for 6 second observation times. Curves fitted to experimental points taken from Blackwell, 1946.

As noted in the introduction, the MR is the range at which very large objects, such as mountains, are just visible through the atmosphere. The term visible range is sometimes used as a synonym for MR. We use MR in this report to specify the atmosphere, and mean to convey a notion of the state of clarity of the atmosphere. Targets, such as the standard target, are usually just detectable at distances much less than the MR. As they recede from view, mountains maintain a large angular size until they disappear because they become too dim to see against the background. As a visual target such as an aircraft recedes it also gets more dim but in addition its angular size decreases so that it becomes too small to see. The combination of these two effects, as manifested in the Tiffany data, determines the range at which the target becomes visible.

PHYSICAL COMPONENT

The basic theory of vision through the atmosphere was developed by Duntley (25). The standard textbook is Middleton (26), and a more recent treatment is given by McCartney (31). The physics behind the appearance of an object seen through an atmosphere involves two primary phenomena. Light emitted from the object toward the observer is partially scattered and absorbed by the atmosphere, thereby weakening the light arriving at the observer from the object. Simultaneously, light from the sun and surrounding atmosphere is scattered into the light path between the object and the observer, thereby producing a veiling illumination that serves to obscure the object. The veiling illumination is produced even if the object is black and is responsible for the disappearance of mountains and other large dark objects at sufficiently large distances. From this, one can calculate the apparent contrast between the object and the background as a function of

the distance from the object to the observer. The distance at which this contrast falls to the threshold level revealed by the Tiffany data is then the critical distance or range at which the target is spotted.

Scattering and absorption are wavelength dependent. In our model, tinted sunglasses are accounted for by multiplying the light arriving at the eye by the transmission coefficient of the sunglass at each wavelength. The resulting distribution of light entering the eye is weighted with the CIE luminosity curve to obtain resulting luminances for the target and background from which the apparent contrast is computed. This color-averaged contrast is compared to the threshold contrast from the Tiffany data to determine the range at which the target is spotted.

There are several objections to this procedure. First, we used the 1931 CIE luminosity curve as the best available for representing the luminosity of small objects. However, by the time our standard target reaches the range at which it is just detectable according to our calculation, it is much smaller (less than 10 min of arc) than the domain of validity of the 1931 curve, which is valid at around 2° of arc. We still believe that using the 1931 curve for luminosity of a very small object is less prone to gross error than if a different use was made, such as using the 1931 data to judge the color of the small object.

A second objection is that we are using color-averaged contrasts as comparable to the threshold contrasts of the Tiffany data, which were taken with background and targets having the hue of white daylight. The hue of the target against the sky, and the apparent hue of the scene viewed through tinted sunglasses, should make more of a difference than can be reflected in a color-averaged value for contrast. For example, everything else being equal, an orange target against a blue sky or ocean is easier to see than a gray, black, or white object of the same contrast with the background. This is why rescue apparatus is orange.

Of the two contrasts discussed here, chromatic and luminance, chromatic is two objects having distinguishable color or hue, and luminance is two objects having distinguishable luminance. Middleton (26) argues that, except in some truly extreme circumstances, only luminance contrast is significant when the object is just at the edge of detectability. At that range, the decay of the light from the object combined with the infilling of veiling light renders the apparent hue of the object nearly the same as that of the background. Stated differently, chromaticity contrast between two different objects of the same size disappears before luminance contrast as the objects recede from the observer through the atmosphere. The calculations in our model are based on a black target with intrinsic contrast equal to -1 (see eq. 15) so that reflectivities and orientation of the object with respect to the sun need not be considered. According to Blackwell (27), the threshold-detection contrast is the same for positive and negative contrasts. For other values of contrast, 'gray' objects, the values of the range at which the object is just detectable will be different.

A serious objection may arise concerning the use of the Tiffany data with highly tinted sunglasses. The question is, to what degree do the luminance contrast thresholds depend on the hue and purity of the background. If there is a significant dependence, because the ideal sunglasses are so strongly tinted, and because the parameter used to evaluate the sunglass is the detection range of the target through the sunglass (tinted scene) compared to the detection range with the naked eye (untinted scene), it may be difficult to estimate the effect of this dependence on our results. In the absence of tinted Tiffany data, the final arbiter of the performance of the sunglass will be experience in the field. On the other hand, our preliminary observations with filters that approach the ideal of this report indicate that if they are not the absolute best sunglass, they are very good sunglasses that do indeed allow detection of typical targets at ranges significantly longer than possible with the naked eye.

The Duntley-Middleton theory, in the form appropriate for wavelength dependent effects (26, p. 157), has light arriving at the observer from the object via

$$B = E_a(1 - e^{-f(r)}) + B_o e^{-g(r)} \quad (7)$$

where B is the apparent radiance of the object, B_a is the radiance of the atmosphere, B_o is the intrinsic or close-up radiance of the object, r is the slant range at which the object is seen, $g(r)$ represents the effect of scattering and absorption of the original light from the object, and $f(r)$ represents the scattering of light from the surrounding atmosphere into the light path. Each of the B 's is radiance per unit wavelength, so that $B d\lambda$ represents the radiance at the wavelength λ within the range $d\lambda$. Each of the B 's is, in general, a function of the wavelength, $B = B(\lambda)$. The functions f and g also depend on the wavelength.

The second term in equation (7) represents light emitted from the object toward the observer, some of which is scattered out of the light path by the intervening atmosphere. The first term represents light scattered into the light path from the surrounding atmosphere, including direct sunshine if present. We were concerned about what to use for B_a , which represents the distribution of light from the sunlight and surrounding atmosphere scattered into the path. On an overcast day, away from the ground, where the atmosphere has the same radiance distribution in all directions, the choice of B_a is unambiguous. On a clear day with blue sky above a white haze horizon, a green or brown earth, and the sun at mid elevation, the radiance distribution of the atmosphere becomes a highly directional quantity, and the choice of B_a is more difficult. The first term on the right in this equation should represent some 'integrated-over-direction' contribution of atmospheric light. We chose CIE D65 daylight for B_a because D65 has a spectral distribution roughly that of the sun in the visible range of wavelengths.

The central simplifying assumption of the Duntley-Middleton theory is that $f(r) = g(r)$. Given that $g(r)$ represents light scattering out of a beam of light and $f(r)$ represents scattering into the beam *by the same scattering mechanism*, the two should behave alike and should be equal. Nonetheless, significant *absorption* of light by a "dirty" atmosphere would make $g(r)$ different from $f(r)$. Although this assumption sounds plausible, it has never, to our knowledge, been verified. The agreement between this theory and the experience of many observers, such as forest rangers and lighthouse keepers, on visibility of objects (26) indicates that this simplifying assumption is sufficiently accurate for the purpose here.

With this simplification, the formula for B becomes

$$B = B_a(1 - e^{f(r)}) + B_o e^{f(r)} \quad (8)$$

In general, $f(r)$ should be represented by an integral along the actual, generally curved, path of the rays that travel from the object to the observer.

If the object and observer are at the same altitude, a short distance apart, and with no conditions such as thermal inversions, etc., it is probably sufficiently accurate to say that the rays of light travel along straight lines in a homogeneous environment that has the same scattering properties throughout its length. Under these conditions, $f(r)$ will have the form

$$f(r) = -\beta r \quad (9)$$

where β is the absorption coefficient. Then the formula for the apparent luminance of the object at a distance r from the observer, becomes

$$B = B_a(1 - e^{-\beta r}) + B_o e^{-\beta r} \quad (10)$$

which is the form we have used.

Except for pure Rayleigh scattering, the wavelength dependence of the scattering coefficient β is quite complex and is not well known analytically for realistic atmospheres. The customary assumption, and the one made here, is to assume Rayleigh scattering of the form,

$$\beta = K\lambda^{-n} \quad (11)$$

where λ is the wavelength, but to substitute different values for the constant K and exponent n than Rayleigh values. In pure Rayleigh scattering, n has the value $n = 4$. In real atmospheres, the effective value of n is less than 4. The effective value of n is what we call the Rayleigh exponent.

In general, the higher the water vapor and aerosol content the smaller value of n until for sufficiently foggy atmospheres, n will be nearly zero and perhaps negative (26, Section 3.3.3). The largest value of n actually measured was slightly larger than 2 on what Middleton called an extremely clear day. It is clear that there should be some correlation between the value of n and the state or clearness of the atmosphere, which is characterized by the meteorological range MR .

Middleton (26, page 45) quotes an empirical formula suggested by Lohle to fit data from 1 to 6 km for MR . The formula is

$$n = 0.0585 (MR)^{1/2} \quad (12)$$

with MR in meters. This formula appears reasonable, in that n gets larger with MR and has reasonable values within the range of data used. Even outside this range, for MR out to 100 km or so, n has values which are fairly reasonable. At $MR = 100$ km this formula produces $n = 2.7$, which is comfortably below the pure Rayleigh value of $n = 4$, and not too far above Middleton's value for a very clear day of $n \approx 2$. We have, therefore, used this formula to relate the Rayleigh exponent to MR .

Nevertheless, this formula should be regarded only as a convenient guess. It has no theoretical foundation whatsoever. This is particularly dangerous if the formula is to be used to extrapolate beyond the available data, which is what we are doing here. Furthermore, the data upon which the formula is based have considerable scatter, suggesting that instead of a simple analytic relationship between n and MR , n depends on other variables in addition to MR or there is merely a statistical correlation between n and MR . Though the use of this formula is one of the weaker tactical points of the calculation, it is something whose effects can be checked by using modified formulas or tabular relationships between n and MR . Doubtless, the target detection ranges will change as this formula is changed, but our supposition and expectation is that the percentages we calculate, by which target detection range through the sunglass is compared to target detection range with the naked eye, will depend only weakly on which formula is used.

The calculation now proceeds as follows. Equation 10 is interpreted to be wavelength specific. The B 's and β depend on the wavelength λ , and the B 's are interpreted as radiances. $B = B(\lambda)$ is the radiance of wavelength λ arriving at the observer from the target. After passing through the sunglass with transmission function $T = T(\lambda)$, the radiance arriving at the eye is $B'(\lambda)$. Multiplying this by the luminosity curve $y = y(\lambda)$ and integrating over wavelength, we get the luminance of the target, B'' ,

$$\begin{aligned}
B'' &= \int y B' d\lambda \\
&= \int y T B d\lambda \\
&= \int y T \{ B_a (1 - e^{-\beta r}) + B_o e^{-\beta r} \} d\lambda
\end{aligned} \tag{13}$$

where $y = y(\lambda)$ is the luminosity curve.

If the target is seen against a background with radiance $B_1 = B_1(\lambda)$, then the apparent luminance B_1'' of the background seen through the sunglass is, by the same token,

$$\begin{aligned}
B_1'' &= \int y T B_1' d\lambda \\
&= \int y T \{ B_a (1 - e^{-\beta r}) + B_1 e^{-\beta r} \} d\lambda
\end{aligned} \tag{14}$$

The apparent contrast, C'' , of the target against the background is defined to be

$$C'' = \frac{B'' - B_1''}{B_1''} \tag{15}$$

This contrast is equated with the threshold contrast of the Tiffany data.

The radiance of the background, B_1 , is treated as distinct from the radiance of the atmosphere, B_a , which scatters into the light path between the target and the observer. This is so that the target can be treated as seen against different backgrounds, clouds, ocean, mountains, et cetera. In this report, we have taken $B_1 = B_a$, simulating the background as the sky itself with the same spectral distribution of radiance as the atmosphere. For the atmospheric radiance, we have taken the spectral distribution to be the CIE D₆₅ standard daylight white, as stated earlier. The 65 in D₆₅ refers to the correlated color temperature of the source or 6504 °Kelvin (12). On a clear day with the sun as the primary source of scattered light, it is probably appropriate to use 6500°K as the color temperature for B_a as well as for B_1 if the target is viewed against the horizon where haze will make that part of the sky approximate the color temperature of the sun. If the target is to be viewed against a part of the sky that is blue, a more appropriate color temperature would be 15000- 30000 °K for B_1 . Likewise, should the target be viewed against the ground, something describing the spectral distribution of the ground would be more appropriate.

In order to simplify equation (17), to follow shortly, we now introduce the wavelength dependent intrinsic contrast of the object

$$C_o = C_o(\lambda) = \frac{B_o - B_1}{B_1} \tag{16}$$

where, as in the previous paragraphs, C_o is the wavelength-dependent intrinsic (close-up) contrast of the object. This is the contrast of the object against the background, seen close-up, wavelength by wavelength. For a black object, where $B_o = 0$, C_o is independent of wavelength and C_o equals -1. A gray object is defined to have C_o independent of wavelength. We define a grey object to have the same spectral composition as the background against which it is seen.

In this report we use the simplifying assumptions that $B_1 = B_a$ and that C_0 is independent of λ . Thus, we will be viewing the object against that portion of the sky having the same spectral composition as the veiling light scattered into the light path. Setting $B_1 = B_a$ simplifies equation (14) to

$$B_1'' = \int yTB_a d\lambda. \quad (14')$$

If we also express B_0 in terms of C_0 , $B_0 = B_1(1 + C_0)$, then equation (13) is transformed into

$$B'' = \int yTB_a(1 - C_0 e^{-\beta r}) d\lambda. \quad (13')$$

With these assumptions, the formula for the apparent contrast of the target C'' , equation (15), simplifies to

$$C'' = \frac{C_0 \int yTB_a e^{-\beta r} d\lambda}{\int yTB_a d\lambda}. \quad (17)$$

This is the formula used in this report. The value C'' depends on r through the exponential term in the integrand on the numerator. This formula is valid with C_0 independent of λ , representing any gray object. If the object is not grey, C_0 would be inside the integral sign. In this study, we use C_0 equal to -1 for a black object, y is the spectral luminosity curve of the eye, T is the spectral transmission function of the sunglass, and B_a is the D_{65} daylight curve. β is the wavelength-dependent scattering coefficient defined in equation (11) with n given by equation (12).

To get the value for K to use in the expression for β in equation (11), we return to the definition of metrological range, MR (26, p 105). For a black object, the MR is defined to be that value of r for which the relative contrast, C''/C_0 , falls to the value .02 for the naked eye. Using the naked eye corresponds to assigning $T=1$ to the sunglass transmission function in equation (17). Therefore, we calculate the value of K to be such that

$$.02 = \frac{\int yB_a e^{-\beta r} d\lambda}{\int yB_a d\lambda} = \langle e^{-\beta r} \rangle \quad (18)$$

where we set $r=MR$ and $\beta = K/\lambda^n$. For n , we use the Lohle value of equation (12). Taking the logarithm of both sides of equation (18) yields

$$\text{Ln } .02 = \text{Ln } \langle e^{-\beta r} \rangle. \quad (19)$$

With an error of negligible significance for the cases considered here, we may write

$$\text{Ln } \langle e^{-\beta r} \rangle \approx \langle \text{Ln } e^{-\beta r} \rangle = -K MR \langle \lambda^{-n} \rangle, \quad (20)$$

where

$$\langle \lambda^{-n} \rangle = \frac{\int yB_a \lambda^{-n} d\lambda}{\int yB_a d\lambda}. \quad (21)$$

For $\text{Ln } .02 = -3.912$ we may solve equation (19) by

$$K = \frac{3.912}{MR \langle \lambda^{-1.1} \rangle}. \quad (22)$$

This value of K is accurate for most of the cases considered here. For greater accuracy this value may be used as the starting value for a successive approximation procedure to solve equation (19).

The range at which the target is spotted is calculated from equation (17), which gives the observed contrast $C'' = C''(r)$. The observed contrast can then be placed in conjunction with equation (4) to get the threshold contrast $C = C(r)$. The range at which the target is spotted is that range r such that $C''(r)$ equals $C(r)$. We numerically perform the equivalent of plotting C and C'' versus r to determine where the curves cross.

THE SUNGLASSES

The spectral transmission of the sunglass, $T = T(\lambda)$, enters into equation (17). Note first that the spotting range of the naked eye can be found by using $T = 1$. We can compare this to the spotting range of the standard 12% transmission neutral density filter by using $T = 0.12$.

Experience and folklore (18, 19) indicate that sunglasses that cut off the blue end of the spectrum seem to enhance visual performance for the wearer. The so-called "Blue Blockers" are based on this idea. In order to examine this genre of sunglasses with some generality we used a convenient analytic expression for T in the form (see figure 4)

$$T(\lambda) = \frac{M}{2} \left[1 + \tanh \left(\frac{\lambda - \lambda_0}{hw} \right) \right] \quad (23)$$

where

M = maximum transmission,

λ_0 = cutoff wavelength,

hw = half-width of the cutoff.

By varying M , λ_0 , and hw , a wide variety of model sunglasses can be examined. Choosing $hw = 0$, allows $T(\lambda) = 0$ or M for $\lambda < \lambda_0$ or $\lambda > \lambda_0$, respectively. We varied λ_0 over the visible wavelengths for fixed values of the parameters M , hw , and MR (metrological range) and calculated the spotting range r as we went. We compared the spotting ranges thus calculated with the spotting range calculated for the naked eye at the same MR . The results are presented in Figs. 5-7.

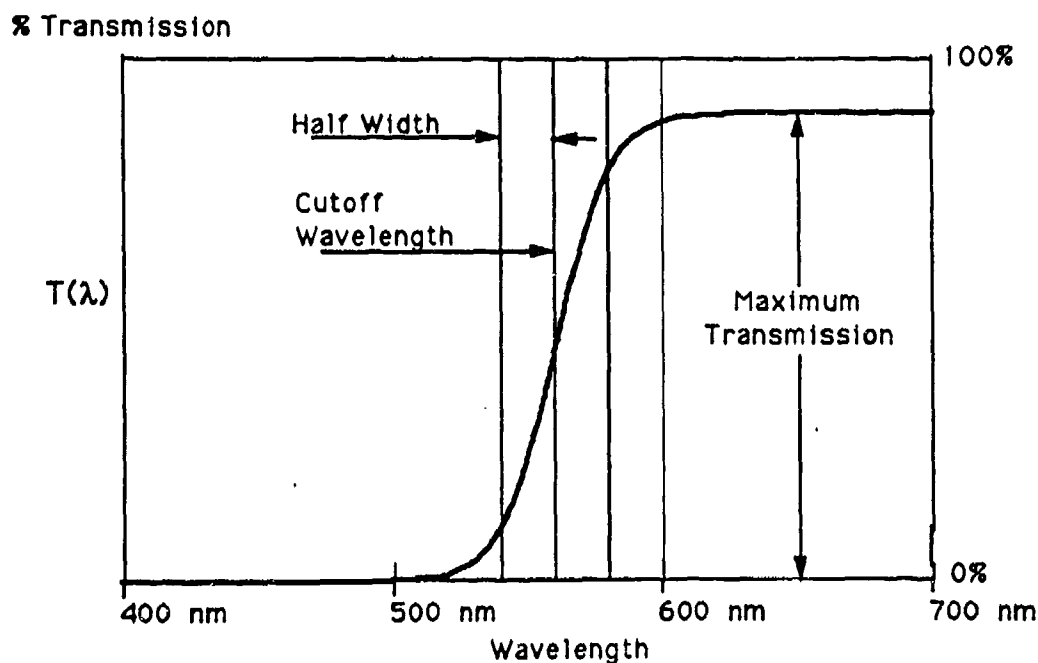


Figure 4. Model sunglass transmission curve parameters, % transmission vs wavelength.

In Figs. 5 - 7, the vertical axis (S/E) indicates the spotting range through the sunglass (S) relative to the spotting range with the naked eye (E). The axis marked Cutoff Wavelength shows λ_0 varying from 400 nm to 688 nm. As λ_0 goes much beyond 688 nm, the portion of the sunglass-transmitting function that is in the visible range of wavelengths is the part that has 0% transmittance, so the spotting range with the sunglass (S) ultimately falls to zero. On the other hand, when λ_0 is at 400 nm, the sunglass transmittance is constant at the value of M , the maximum transmittance, except for a region of width hw near 400 nm. Under these conditions the spotting range is the same as for a neutral density sunglass having a transmittance factor equal to the value of M . For $M = 100\%$ this will be the spotting range for the naked eye.

Figure 5 depicts the results for "Ideal" sunglasses, which have $M = 100\%$ transmission and $hw = 0$ (sharp cutoff). As the cutoff wavelength λ_0 varies from 400 to 688 nm, we see a range of cutoff wavelengths for which S can exceed E by factors of from 4 to 6%. The critical value of λ_0 that maximizes S/E depends on the meteorological range MR . These critical values are shown in Table 2 below. Note, however, that λ_0 can vary 10 or 20 nm on either side of the critical value without seriously degrading the performance of the sunglass.

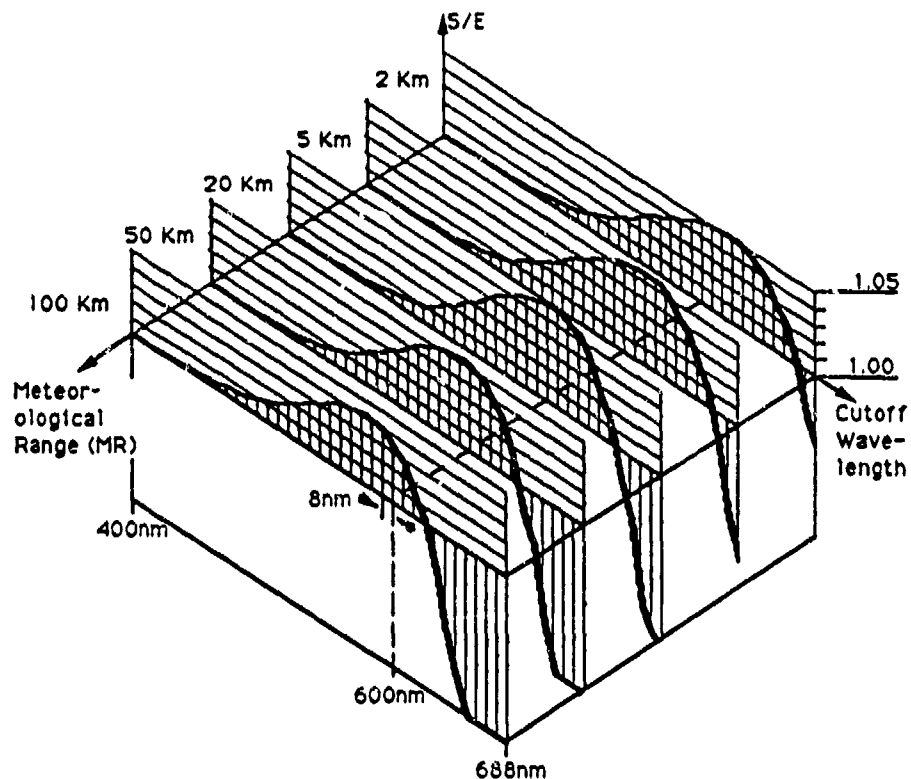


Figure 5. Ideal (sharp cutoff, 100% maximum transmission) sunglass performance vs meteorological range.

We find these "Ideal" sunglasses with λ_0 having the critical value out perform every other sunglass in the family of sunglasses represented by equation (22). Figure 6 compares sunglasses with different values of hw for $M = 100\%$ and $MR = 20 \text{ Km}$. The best performance is degraded as hw increases but not seriously until hw goes beyond 10 nm . This is significant because "sharp cutoff" filters are available which have the cutoff half width within 10 nm .

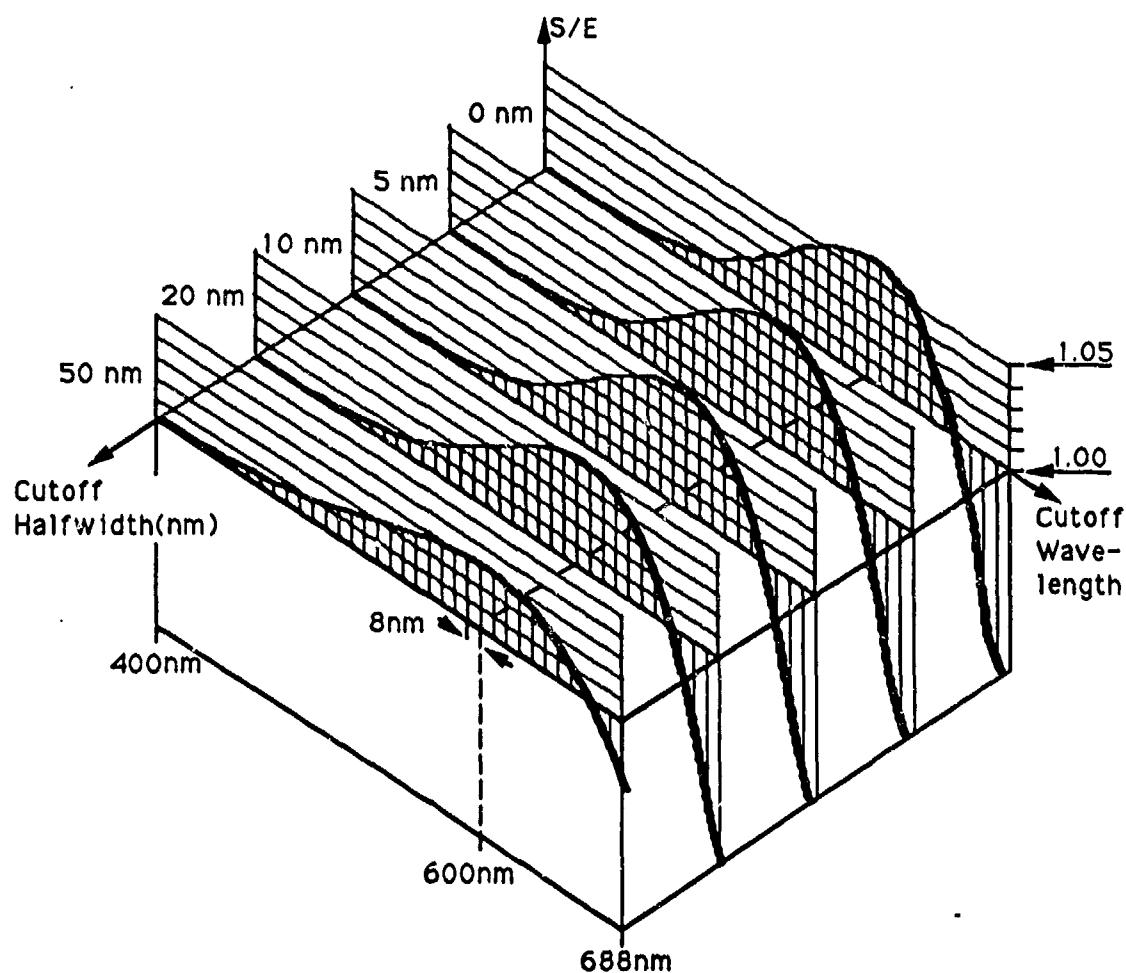


Figure 6. Sunglass (100% maximum transmission) performance vs cutoff half-width at MR equal to 20 km.

Figure 7 compares sharp cutoff ($hw = 0$) sunglasses with different values for M also at $MR = 20$ km. Here, performance degradation is much more severe as M decreases from the maximum value of 100%. Still, the performance of the $M = 90\%$ at its critical λ_0 sunglass is only slightly inferior to the ideal sunglass operated at its critical value. The significance of this is that "sharp cutoff" filters are available with maximum transmission better than 90% and minimum transmission indistinguishable from 0%. With the cutoff wavelength properly selected for the conditions (value of MR), these filters should perform nearly as well as the "Ideal" sunglass with λ_0 selected at the critical value.

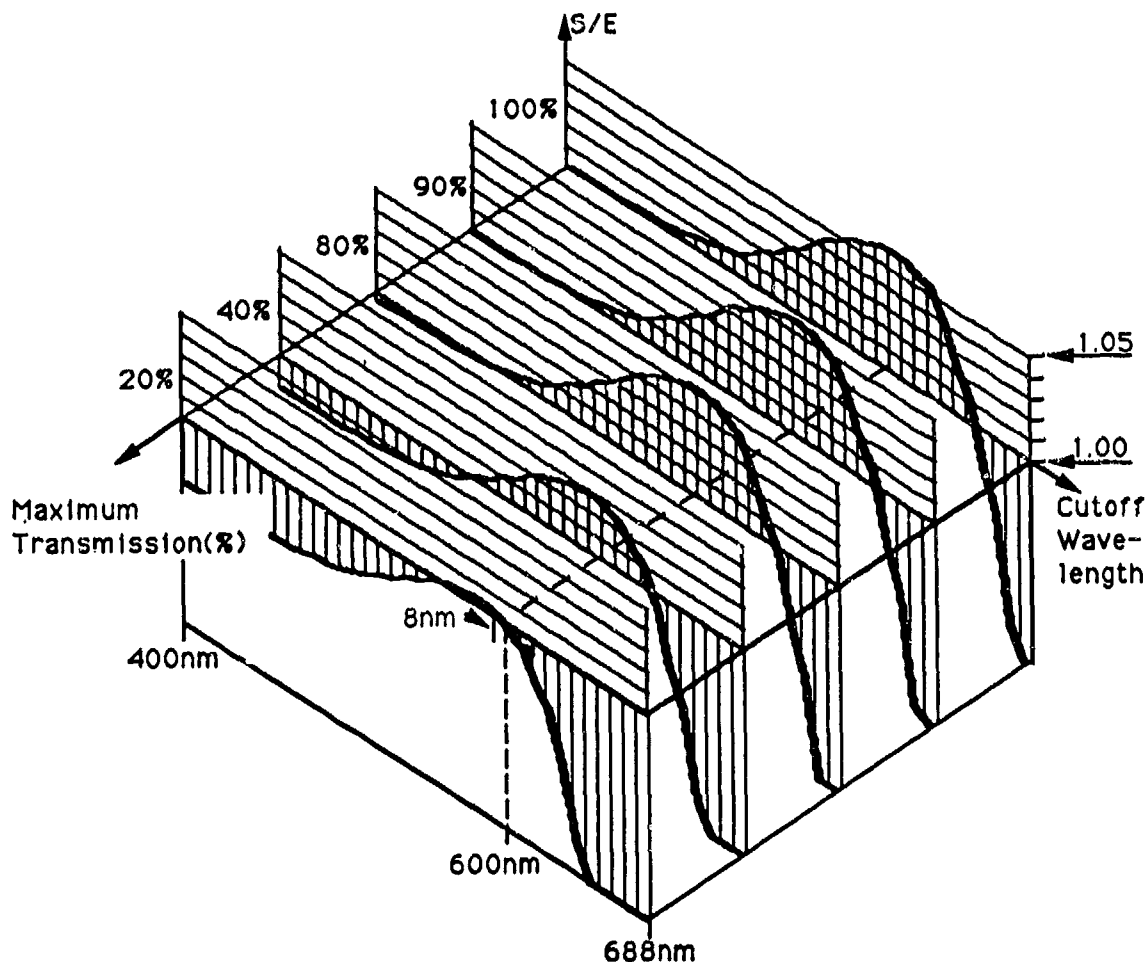


Figure 7. Sunglass (sharp cutoff) performance vs transmission maximum at MR equal to 20 km.

Figures 5-7 allow a rather simple physical interpretation that may be useful as a guide for situations not treated here. On the one hand, the Blackwell data show that a brighter background furnishes more favorable circumstances to detect an object at the limit of visibility. Anything that reduces the background luminance without altering the contrast between the object and background will degrade spotting performance. On the other hand, light scattered into the light path will reduce contrast and hence performance. This happens more for blue than red light, so in general performance is enhanced by discarding shorter wavelengths.

The fact that the "Ideal" sunglasses (sharp cutoff sunglasses with 100% maximum transmission) perform better than any other sunglass suggests that we think of the visible spectrum as being divided into "good" and "bad" wavelengths separated by the critical wavelength λ_0 . The "bad" wavelengths are on the blue side of λ_0 and are bad because they scatter too strongly into the light path, reducing the contrast of the object more than they enhance the brightness of the background. The "good" wavelengths are on the red side of λ_0 . They are good because their scattering into the light path is so weak that they enhance the brightness of the background more than they reduce the contrast of the object. Thus, the ideal sunglass is the best possible because it lets through all the "good" wavelengths and rejects all the "bad" wavelengths. The precise value of λ_0 depends on how much more strongly the blue wavelengths are scattered than the red, that is to say on the MR, and the interplay of this relationship with the luminosity curve of the eye.

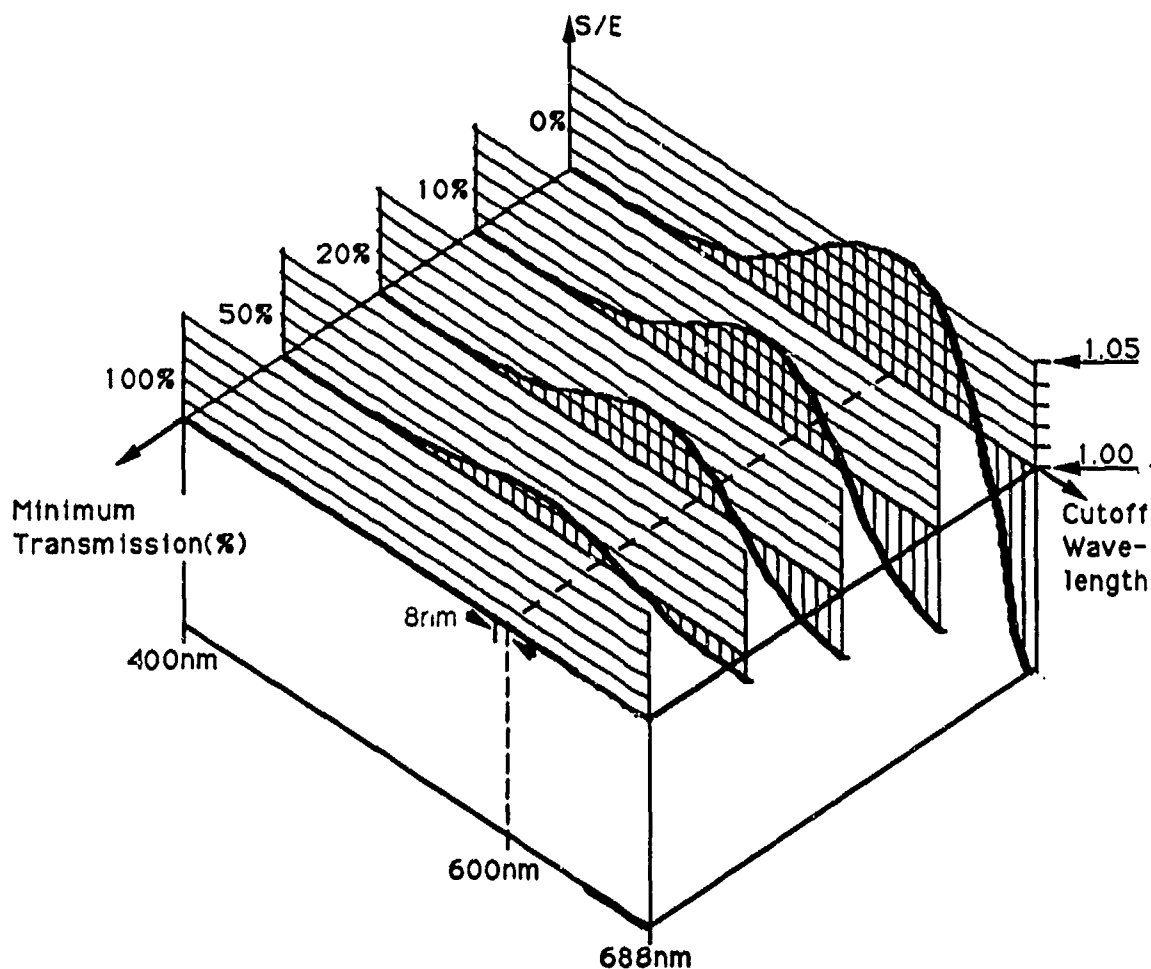


Figure 8. Effect of lifting the transmission percentage on the cutoff side of sharp cutoff sunglasses. When the minimum transmission is 100% there is no effective cutoff and no resultant effect.

As seen in Fig. 5, when the cutoff wavelength is at 400 nm and beyond, the sunglass is completely transparent everywhere in the visible spectrum, and the performance is like that of the naked eye. As the cutoff wavelength is moved toward the red, the performance of the sunglass improves as the strongly scattered blue wavelengths are excluded.

Where the cutoff wavelength is in the red, the wavelengths admitted to the eye are weakly scattered but are far out on the limb of the visibility curve. The resulting background luminance is faint, and the performance suffers because faint backgrounds require higher threshold contrasts. As the cutoff wavelength moves in from the red toward the blue end of the spectrum, the performance rises in spite of admitting more of the strongly scattered shorter wavelengths because the climb up the side of the visibility curve rapidly brightens the background. The rapid brightening of the background in this region is more effective in increasing the sensitivity to contrast than the admittance of the shorter wavelengths is in lowering the contrast.

Performance suffers when the half width (hw) of the cutoff is increased (Fig. 6) because some of the "bad" wavelengths are let in and some of the "good" wavelengths are partially blocked. Performance suffers

when the maximum transmission (M) decreases because all the "good" wavelengths are blocked to some extent.

This interpretation shows why a narrow bandpass sunglass, with the pass band out in the red, is not the best sunglass for spotting at extreme ranges. Such a sunglass blocks some of the "good" wavelengths, which could brighten the background and allow detection of an angularly smaller and hence more distant target.

Finally, we take a look at what happens when some leakage of light on the blue side of the cutoff wavelength is allowed. This is because some brands of so called "Blue Blockers" allow a considerable amount of blue light through the sunglass, though much less than the red end. This is no doubt to preserve some semblance of color balance in the scene. We take the Ideal sunglass and lift the transmission curve on the cutoff side so that below the cutoff wavelength, a constant minimum transmission is allowed. The maximum transmission is kept at 100%. Figure 8 shows that allowing some of the blue light below the cutoff wavelength through the sunglass rapidly degrades performance as a spotting sunglass relative to the best possible. This is consistent with our picture that admitting the "bad" wavelengths degrades spotting performance.

RESULTS

The first result of our investigation shows that neutral density sunglasses in general, and 12% neutral density sunglasses in particular, degrade vision compared to the performance of the naked eye in the sense that the standard target can be detected further away with the naked eye than with neutral density sunglasses. In the case of a MR of 100 km, the standard target can be spotted at a range of 19.58 km with aviator sunglasses, but an observer with only his naked eye will spot the target 1.53 km farther away. The results for other MR s are shown in Table 1.

Table 1 shows that at MR s in excess of 30 km or so, (corresponding to operational spotting ranges greater than about 12 km), the operator using his naked eyes can spot our standard target at a distance 5% or more farther away than he can wearing 12% neutral density filters. Neutral density sunglasses always degrade the ability to detect distant objects. When viewing an object through the atmosphere with the help of neutral density sunglasses, the sunglasses cut down the light entering the eye both from the surrounding atmosphere and from the object by the same percentage. The apparent contrast between the object and the surround is unchanged. As discussed in the introduction, visual acuity is not strongly affected by lowering the light level, as long as that light level remains above a certain value. However, according to Blackwell's data (27), the threshold contrast at which an object of given angular size is just detectable increases as the background luminance decreases. Therefore, if an object is just detectable at a certain distance by the naked eye, it will be invisible through neutral density sunglasses.

Table 1. Performance of 12% neutral density sunglasses.

Meteorological range (km)	Naked eye detection range (km)	12% ND filter detection range (km)	Difference (km)	Percent difference
100	21.11	19.58	1.53	7.2
50	15.99	15.00	0.99	6.2
20	10.02	9.57	0.45	4.5
5	4.10	3.99	0.11	2.7
2	2.05	2.01	0.04	1.9

With tinted sunglasses of appropriate design, however, it is theoretically possible to see objects at a greater distance than with the naked eye. This is because tinted sunglasses can filter out the shorter wavelengths, where contrast-reducing scattering is strongest, and leave the longer wavelengths. The only difficulty is to find the optimal cutoff wavelength. The ideal sunglass is 100% transmitting above (on the red side) a cutoff wavelength and 100% absorbing below. Table 2 shows results for the ideal sunglass with the cutoff wavelength optimized for different MRs.

Table 2. Performance of ideal sunglasses.

Meteorological range (km)	Cutoff wavelength (nm)	Naked eye detection range (km)	Ideal sunglass detection range (km)	Difference (km)	Percent difference
100	576	21.11	22.04	0.93	4.4
50	592	15.99	16.85	0.86	5.4
20	600	10.02	10.61	0.59	5.9
5	616	4.10	4.33	0.23	5.6
2	616	2.05	2.15	0.10	4.9

According to Fig. 5 we see that the ideal sunglass, optimized for each condition by adjusting the cutoff wavelength, allows the target to be seen 5% or more farther away than the naked eye, except at the longest range where the number drops to 4%. The maximum range is nearly achieved for quite a wide spread of cutoff wavelengths, ± 10 to 20 nm, so that an ideal sunglass optimized for 50 km MR with a cutoff wavelength of 592 nm would work quite well for all the MRs calculated from 2 to 100 km.

Practical filter materials will not, of course, behave as the ideal sunglass. However, filters are available that permit sunglasses to be made that significantly enhance the performance of the naked eye. Several filters are available with a flat maximum transmission of around 90% and a transition to virtually 0% transmission over a range of 10 nm or so. In Table 3, we present the performance of a family of practical sunglasses, which have a transmission curve in the shape of a hyperbolic tangent curve (cf the computation section). The maximum transmission M is 80%, which is somewhat less than the maximum available. The transition from maximum to minimum transmission occurs over a range of 10 nm so that $hw = 5$ nm. The cutoff wavelength is the wavelength at which the transmission is half of its maximum value.

Table 3 shows that practical sunglasses could improve performance by 3.4-5.1% at all ranges, but describes different sunglasses optimized for different MRs. For each MR, a different critical cutoff wavelength, λ_0 , produces the best achievable performance. Indeed, it may be desirable to have different sunglasses optimized for different conditions.

Table 3. Performance of practical sunglasses.

Meteorological range (km)	Cutoff wavelength (nm)	Naked eye detection range (km)	Practical sunglass detection range (km)	Difference (km)	Percent difference
100	576	21.11	21.83	0.72	3.4
50	584	15.99	16.71	0.72	4.5
20	600	10.02	10.53	0.51	5.1
5	608	4.10	4.31	0.21	5.1
2	616	2.05	2.14	0.09	4.4

For a single observer in a rapidly changing environment a single sunglass that will perform adequately under all conditions may be desirable. Fortunately, this requirement is not too difficult to meet. If our practical sunglass is chosen with a cutoff wavelength of 580 nm, which is nearly optimum for 100 km MR, the improvement over the naked eye detection range will be at least 3% all the way down to a MR of 2 km.

Finally, we note that the retina of an eagle incorporates oil droplets of spectral transmission closely resembling the transmission curve used for our ideal sunglass (fig. 4). The oil has a maximum transmission M of around 85% and an hw of about 25 nm. Thus, the eagle's eye seems to be designed for spotting at long distances. The cutoff wavelength is about 530 nm, which is farther toward the blue than a similar sunglass optimized for spotting by humans would be. Presumably this is at least partly due to a difference in the luminosity curves of humans and eagles.

At least one commercial sunglass has a transmission curve inspired by the eagle, according to advertising. It resembles the curve of fig. 4, with a maximum transmission M of about 90% and an hw of about 25 nm. These glasses have the cutoff wavelength closer to the optimum value for spotting appropriate to humans. The advertising includes reports from gliding pilots, soaring pilots, and commercial aviation pilots attesting to their ability to spot objects at distances farther than is possible with competing sunglasses.

SUMMARY AND RECOMMENDATIONS

The ideal sunglass is optimized for target detection by military aviators. Serendipitously, it also turns out to be fairly close to the ideal in terms of glare protection and target identification (acuity). The transmission figure of 12% for a military standard neutral density sunglass was presumably chosen, if only crudely, to maximize eye comfort (i.e., to reduce glare to a comfortable level in a bright environment). The ideal sunglass, optimized for 100 km MR, has a net transmission of 30%, and the practical sunglass, based on readily available filter materials, has a net transmission of 25%. If the standard neutral density sunglass is anywhere near the ideal transmission for optimum glare reduction, then so is the ideal sunglass.

These calculations and predictions are based on the human's ability to detect contrast, not acuity. In fact, the model predicts that acuity is relatively unaffected by the spectral characteristics of the filter. This prediction agrees with most of the studies in the literature; shooter's glasses and other spectral filters generally do not improve acuity (18,20,21). Such results have generally been interpreted to demonstrate the visual ineffectiveness of these filters. The opposite may be the case. Our calculations predict that spectrally non-neutral filters could enhance contrast detection, not acuity. Past performance tests of the effect of filters may have actually been measuring the wrong parameters.

Studies at the Naval Submarine Medical Research Laboratory, New London, have consistently demonstrated the visual effectiveness of selected yellow tinted filters in improving or enhancing visual reaction time, depth perception, and contrast detection (32-37). The authors interpreted their results in terms of an opponent-process theory of the neurophysiology of color vision (36,37). We have addressed factors external to the eye in this report; they addressed events following phototransduction of light energy to neural signals. Both theories may be correct, and the improvement in vision with appropriately chosen filters may be better than either theory alone would predict.

The glaring defect of the ideal sunglass is the total rejection of green and blue wavelengths. The practical filters available, which approximate the ideal sunglass, do the same; blue and green areas appear black. This is not necessarily a universally bad thing. The alteration of contrasts from normal can enhance the detection of some objects, for example, in the case of orange lifesaving equipment in a blue ocean. The emotional effect produced by the altered contrast, familiar to many wearers of the so-called "Blue Blockers," is amplified by the ideal sunglass. Nevertheless, careful scrutiny of the interaction between the ideal sunglass

and the various signal lights, panel lights, and heads-up displays will be necessary. It may be necessary to redesign some phosphors in displays, and/or allow certain pass bands in the sunglasses.

We note here that we have made a pair of glasses from filters that approximate the ideal sunglass. Although these glasses are very effective at spotting airplanes at distances beyond the capabilities of the naked eye, they are not very satisfactory for driving around town. That is, brake lights on cars ahead are much enhanced, but the general scene is rather washed out due to the exclusion of the blues, greens, and yellows. Sunglasses optimized for spotting targets at maximum range are not very good at enhancing contrasts between typical objects at ordinary ranges. This anecdotal evidence supports our contention that optimization of sunglasses for a given task requires criteria appropriate to that task.

There is now a theoretical basis for considering the use of color in sunglasses. The effects of tinted lenses on color appearance and wavelength discrimination also need to be addressed. Studies of color appearance through colored filters are surprising; they consistently show that filters have little effect. In other words, objects seen through the filters tend to maintain their normal color appearance (38,39). Although this may at first be astonishing, it is consistent with the well known facts of color constancy. Again, the mechanisms for color constancy are not well understood, but the point is that there are reasons to reevaluate the common wisdom that colored filters are a hazardous disruption of normal color vision.

The following requirements could be incorporated into a practical military specification (MILSPEC) for sunglasses that would have some advantages over standard neutral density filters.

- a. The sunglass should permit detection of a standard target under standard conditions at ranges at least as great, or $x\%$ greater, than that permitted by the naked eye.
- b. The sunglass should permit acuities within 90% of the maximum.
- c. The sunglass should pass no greater than 30% of the light.
- d. The sunglass should be compatible with HUD's.

This work is preliminary, in the sense that we are reporting first results. We have studied only the easiest cases. We also need to study: the robustness of the percentage predictions, cases including slant rather than horizontal ranges, blue sky rather than white sky backgrounds, ocean and desert backgrounds, et cetera, and visors made of material approximating the ideal sunglass.

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